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Electromagnetic Properties of Tissue in the Optical Region

K. M. Yaws[*], D. G. Mixon[†], W. P. Roach[‡]

Air Force Research Laboratory, 8262 Hawks Rd. Bldg. 1162, San Antonio, TX 78235

ABSTRACT

To properly assess skin damage caused by photonic exposure, the mechanisms of photon attenuation and subsequent heat production are investigated. Currently, voids exist in frequency specific electromagnetic properties such as the complex dielectric permittivity and conductivity necessary to define refractive index and attenuation values. We investigate these properties in several tissues such as blood, bone, skin, vitreous humor, cornea, retina and many others. Inside these tissues, exponential decrease in photon energy occurs due to attenuation. Because photon energy absorbed in tissue is expressed as heat in many instances, it follows that the dielectric properties of the material will also change as a function of the heating patterns as well as with frequency or wavelength. Conversely, changes in tissue thermal properties should change photon behavior as dispersion properties change. In our case we are concerned with existing data and theoretically determining dispersion properties over a large range of frequencies or wavelengths.

Key Words: dielectric permittivity, attenuation, optical conductivity

1. Introduction

In order to gain clarity into the historical basis for double Debye usage to describe mechanical excitation and relaxation for polar liquids in the Terahertz frequency range, a literature search is performed and an attempt is made to follow the science from theoretical principals onward. Peter J. W. Debye postulated that mechanical excitation and relaxation occurred according to one relaxation mode.[1] The following equations describe that phenomenon:

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon - \varepsilon_\infty}{1 + i\omega\tau} \tag{1}$$

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{\varepsilon - \varepsilon_\infty}{1 + \omega^2\tau^2} \tag{2}$$

$$\varepsilon''(\omega) = \frac{(\varepsilon - \varepsilon_\infty)\omega\tau}{1 + \omega^2\tau^2}. \tag{3}$$

Where $\hat{\varepsilon}(\omega)$ is the complex permittivity as a function of angular frequency, $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ are the real and imaginary parts of the Debye model, respectively. Also, ε_∞ is the limiting value of permittivity at high frequency, ε is the relative permittivity, and τ is the mechanical relaxation time. While the Debye model describes permittivity data up to the microwave region, at higher frequencies, our ability to predict Debye parameters that correlate with empirical data decreases. Cole-Cole and Cole-Davidson models improved upon Debye's original theoretical model by adding terms describing empirically gathered dielectric permittivity data at frequencies from 35GHz to .5THz, notionally. Bruchner et al posed the following empirically derived equation to describe the complex permittivity of polar liquids at broadband frequencies. The model includes Cole-Cole, Cole-Davidson and single and multiple Debye equations:[2]

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[*] kalyn.yaws@brooks.af.mil; phone 1 210 536 3178; fax 1 210 536 3977; www.afrl.af.mil
[†] dustin.mixon@brooks.af.mil; phone 1 210 536 5094; fax 1 210 536 3977; www.afrl.af.mil
[‡] william.roach@brooks.af.mil; phone 1 210 536 2770; fax 1 210 536 3977; www.afrl.af.mil

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + (\varepsilon - \varepsilon_\infty) \sum_{j=1}^{n} \frac{g_j}{[1 + (i\omega\tau_j)^{1-\alpha_j}]^{\beta_j}} \qquad (4)$$

$$g_j = \frac{\varepsilon_j - \varepsilon_{j+1}}{\varepsilon - \varepsilon_\infty} . \qquad (5)$$

Here $\hat{\varepsilon}(\omega)$ is the complex permittivity as a function of angular frequency, ε_j is the value of epsilon at an intermediate frequency step, ε_∞ is the limiting value at high frequency, ω is the angular frequency $(\omega = 2\pi f)$, τ_j is the mechanical relaxation time at an intermediate frequency step and α and β are Cole-Cole or Cole-Davidson parameters. Kindt et at determined that the double Debye form of Equation 4 provides the best approximation of complex permittivity for polar liquids at frequencies up to 1THz when compared with Cole-Cole and Cole-Davidson.[3] Using the double Debye parameters, $n = 2$, $\alpha = 0$, $\beta = 1$ and $\varepsilon_1 = \varepsilon = \varepsilon_s$ the double Debye used by Pickwell et al is derived.

$$\hat{\varepsilon}(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + i\omega\tau_1} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + i\omega\tau_2} \qquad (6)$$

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \qquad (7)$$

2. Analysis

Because the optical coefficients $n(\omega)$, $k(\omega)$, $\alpha(\omega)$ and $\sigma(\omega)$ are of interest and are based on the real and imaginary components of the complex permittivity, $\hat{\varepsilon}(\omega)$, we rationalize Equation 6 and separate $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$, yielding

$$\varepsilon'(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_2}{1 + (\omega\tau_1)^2} + \frac{\varepsilon_2 - \varepsilon_\infty}{1 + (\omega\tau_2)^2} \qquad (8)$$

$$\varepsilon''(\omega) = \frac{(\varepsilon_s - \varepsilon_2)(\omega\tau_1)}{1 + (\omega\tau_1)^2} + \frac{(\varepsilon_2 - \varepsilon_\infty)(\omega\tau_2)}{1 + (\omega\tau_2)^2} . \qquad (9)$$

Reference	Model	ε_S	ε_2	ε_∞	τ_1 (ps)	τ_2 (ps)
Ref.[4]	Water	78.8	6.6	4.1	10.6	0.18
Ref.[4]	Skin	60.0	3.6	3.0	10.0	0.20
Ref.[5]	Epidermis	58	3.6	3.0	9.4	0.18
Ref.[6]	Ex Vivo	14.7	4.16	2.58	1.45	0.0611

Table 1-Summary of Values Reported by Pickwell et al.

Using the values in Table 1 and Equations 8 and 9, double Debye values for $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ versus frequency (THz) are shown for water, epidermis and dermis in Figure 1.
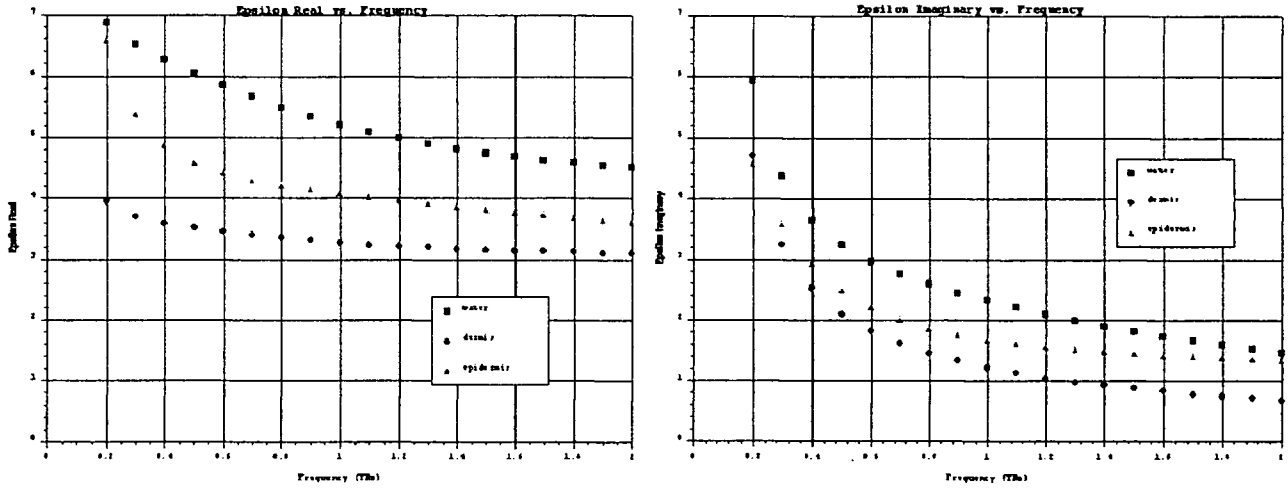
Figure 1-Epsilon Real and Epsilon Imaginary vs. Frequency for water, dermis and epidermis.

Classically[7],

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) = \hat{n}^2(\omega) \tag{10}$$

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - i\frac{\sigma(\omega)}{\varepsilon_0\omega} \tag{11}$$

$$\hat{n}(\omega) = n(\omega) - i\frac{c}{2\omega}\alpha(\omega) = n(\omega) - ik(\omega) \tag{12}$$

Where $\hat{n}(\omega)$ is the complex index of refraction, $n(\omega)$ is the index of refraction, $k(\omega)$ is the extinction coefficient, $\alpha(\omega)$ is the absorption coefficient and $\sigma(\omega)$ is the conductivity. Solving $\hat{\varepsilon}(\omega)$ for $n(\omega)$, $k(\omega)$, $\alpha(\omega)$ and $\sigma(\omega)$ yields Equations 13-16

$$n(\omega) = \left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} + \varepsilon'}{2}\right)^{\frac{1}{2}} \tag{13}$$

$$k(\omega) = \left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{2}\right)^{\frac{1}{2}} \tag{14}$$

$$\alpha(\omega) = \frac{2\omega}{c}\left(\frac{\sqrt{\varepsilon'^2 + \varepsilon''^2} - \varepsilon'}{2}\right)^{\frac{1}{2}} = \frac{2\omega}{c}k(\omega) \tag{15}$$

$$\sigma(\omega) = \varepsilon_0\omega\left[\varepsilon''(\omega)\right]. \tag{16}$$

Where c=2.9979x10^{10}cm/s.

Using the published Pickwell data from Table 1, $n(\omega)$, $k(\omega)$, $\alpha(\omega)$ and $\sigma(\omega)$ versus frequency for water, epidermis and dermis are plotted in Figure 2.
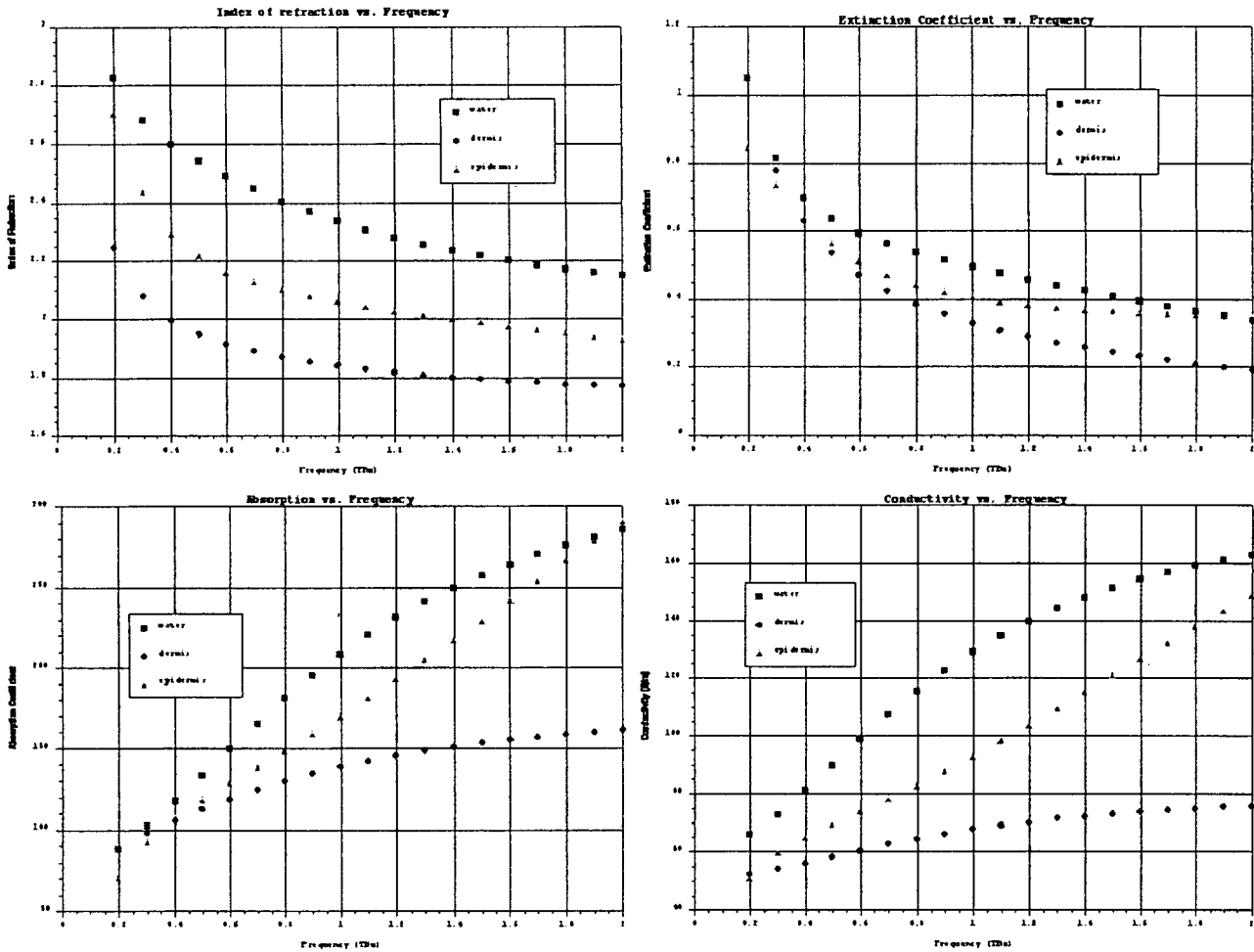
Figure 2-Index of Refraction, Extinction Coefficient, Absorption and Conductivity vs. Frequency for water, dermis and epidermis.

Next, the thermal relaxation time for water, epidermis and dermis is desired. Niemz[8] gives the following equation, which link the absorption coefficient $\alpha(\omega)$ to the thermal relaxation time, τ_{therm} .

$$L = \frac{1}{\alpha(\omega)} = \sqrt{4\kappa\tau_{therm}} \qquad (17)$$

Where L is the attenuation length, sometimes referred to as the mean free path, $\alpha(\omega)$ is the absorption coefficient, κ is the thermal diffusivity, and τ_{therm} is the thermal relaxation time. First the thermal diffusivity,

$$\kappa = \frac{K}{\rho C}, \qquad (18)$$

is calculated using data from Table 3 where K is the thermal conductivity of water, ρ is the density of water and C is the specific heat of water.

	specific heat	density	thermal conductivity	thermal diffusivity
water	4.19	1	0.006	0.0015
epidermis	2.24	1.21	0.002	0.0007
dermis	3.66	1.06	0.005	0.0013

Table 2-Thermal Properties of water, dermis and epidermis.

Now, using Equation 17, the thermal relaxation time is derived.

$$\tau_{therm} = \frac{1}{4\kappa\alpha^2(\omega)} \tag{19}$$

Using data from Table 2 and Equation 19, values for τ_{therm} of water, epidermis and dermis versus frequency are calculated and plotted in Figure 3.
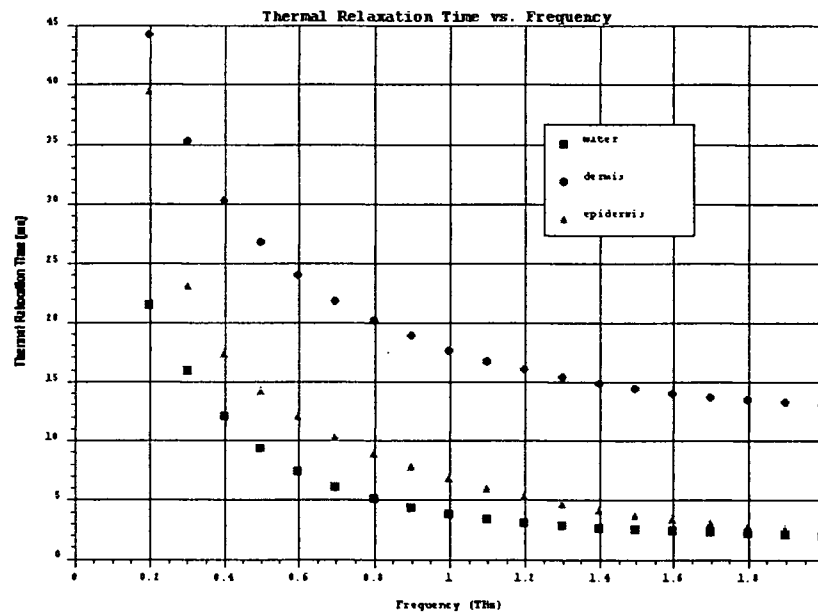

Figure 3-Thermal Relaxation Time vs. Frequency for water, dermis and epidermis.

3. Comparison

To check the validity of the thermal relaxation time for water, a comparison between Pickwell et al and Hale et al water data is performed. Hale et al calculated index of refraction, extinction coefficient and absorption coefficient for water over the entire electromagnetic spectrum.[9] Hale and Pickwell thermal relaxation times for water are compared in Figure 4.

Qualitatively, both the Hale data and the Pickwell data show exponential decay at roughly the same rate. To quantitatively assess the difference between the Pickwell and Hale data, power fits of both sets of data are performed and percent difference between them is calculated. Both sets of data are shown in Figure 4.

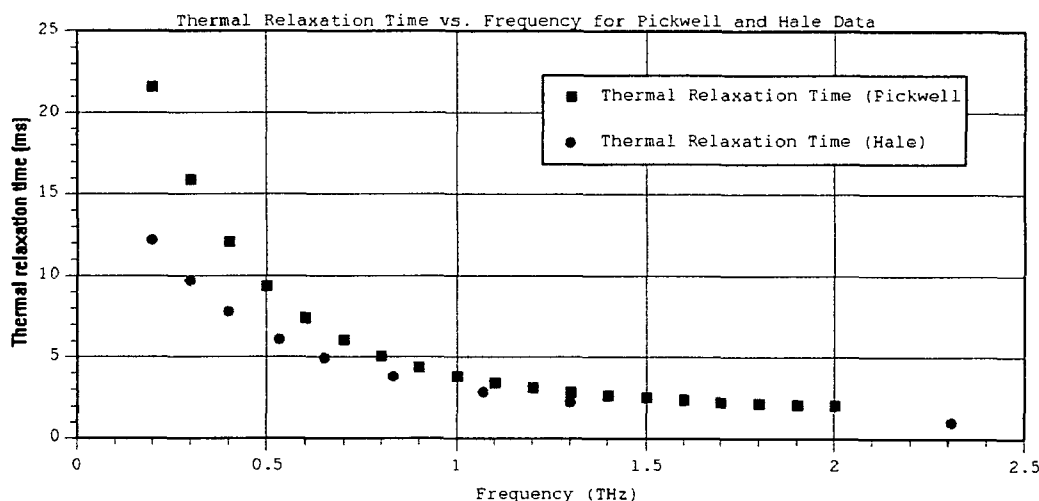Thermal Relaxation Time vs. Frequency for Pickwell and Hale Data

Figure 4-Thermal Relaxation Time (ms) vs. Frequency for Hale et al and Pickwell et al water data. Power fits are also shown.

The calculations show a percent difference between the data sets that ranges from 35% at .2 THz to 14% at 2.31 THz. Also, the Pickwell data shows a thermal relaxation time that is consistently longer than that calculated by Hale.

4. Conclusions

The authors find the Terahertz region of the electromagnetic spectrum interesting scientifically for many reasons, namely in this region of the spectrum, theoretical models of dielectric permittivity appear to break down. In the low frequency range, complex dielectric permittivity is theoretically modeled by Debye; however as the frequency increases errors occur in the Debye model. Past work has sought to rectify this conundrum by adding terms to the Debye model to force the model to fit experimental data, such as work published by Barthel et al. Clearly, in the Terahertz region, more than primarily mechanical excitation is occurring. The authors hypothesize that between 35GHz and upwards of 20 THz, all models break down in their explanation of polarized states leading to mechanical or electronic excitation and relaxation. As mechanical excitation decays it gives rise to electronic transitions described classically by Drude-Lorentz theory, and therefore we are operating in a region of mixed modes of excitation without adequate theory to predict material behavior from electromagnetic exposure. The authors see an opportunity to break new scientific ground by theoretically modeling the transition region between Debye mechanical excitation and Drude-Lorentz electronic excitation that notionally occurs in the Terahertz region.

Acknowledgements

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